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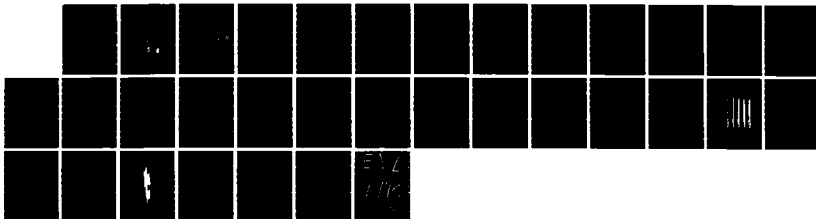
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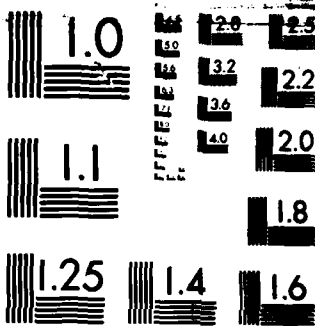
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PERIODIC AMPLITUDE VARIATIONS IN
JOVIAN CONTINUUM RADIATION

by

W. S. Kurth¹, D. A. Gurnett¹ and F. L. Scarf²

March 1986

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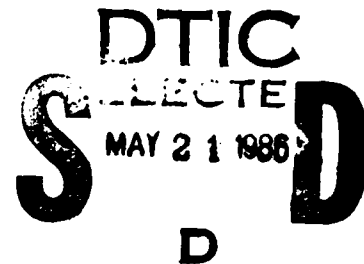
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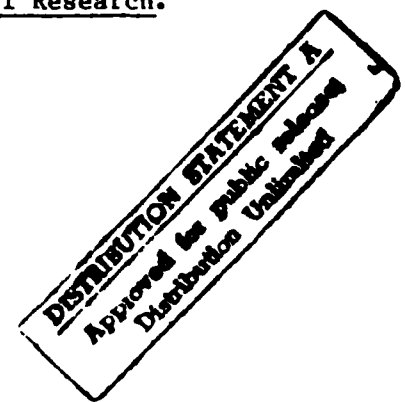
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ABSTRACT

An analysis of periodic variations in the amplitude of continuum radiation trapped in the Jovian magnetosphere shows structure with periods near both five and ten hours. Contrary to a plausible initial idea, the continuum amplitudes are not organized by position of the observer relative to the dense plasma sheet. Instead, there seem to be preferred orientations of System III longitude with respect to the direction to the sun which account for the peaks. This implies a clock-like modulation of the continuum radiation intensity as opposed to a searchlight effect. The importance of the dipole longitude-solar wind alignment to the amplitude of the continuum radiation implies the source region of the radiation is near the magnetopause and may tie the generation of the radio waves to the clock-like modulation of energetic electron fluxes from Jupiter.

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I. INTRODUCTION

The dominant feature in the radio spectrum of Jupiter below 100 kHz is the trapped continuum radiation [Scarf et al., 1979; Gurnett et al., 1979, 1980]. The spectrum is most intense at frequencies below about 5 kHz, the typical solar wind plasma frequency in the vicinity of Jupiter. Below about 5 kHz the radiation is trapped within the density cavity formed by the Jovian magnetopause and the high density regions near the planet, specifically, the Io plasma torus. In the low density lobes of the Jovian magnetotail, the continuum spectrum can extend below a few hundred Hz. Since the spectrum follows an approximate f^{-4} law, observed power fluxes at the lower frequencies can exceed 10^{-12} $\text{Wm}^{-2}\text{Hz}^{-1}$.

Figure 1 shows the electric field spectral density as a function of time for five of the Voyager 1 plasma wave receiver spectrum analyzer channels for a 10-day interval beginning on day 65, 1979. The solid black areas represent 16-minute average values. The averages allow one to see long period amplitude variations as a function of time. Some of the earliest studies of terrestrial continuum radiation [Gurnett and Shaw, 1973; Gurnett, 1975] implied the emission was generally characterized by smoothly varying spectra and little temporal structure. More recent studies [e.g., Kurth et al., 1981], using improved instrumentation, demonstrated the narrowband nature of the continuum spectrum. Gurnett et al. [1981, 1983] showed the narrowband

nature of the emission at both Saturn and Jupiter. Little has been mentioned in the literature about temporal variations in amplitudes, although Scarf et al. [1981] observed 10-hour periodicities in the amplitude of continuum radiation trapped in Jupiter's distant magnetotail, some 6200 R_J downstream from the planet.

It is the purpose of this paper to discuss the quasi-periodic variations evident in the continuum radiation observations shown in Figure 1. An understanding of the variations will lead to a more thorough understanding of the source of the emissions as well as further insight to the various mechanisms which are operative in the Jovian magnetosphere. The observations presented are from the Voyager 1 and 2 plasma wave receivers which are described by Scarf and Gurnett [1977].

II. PERIODIC VARIATIONS OF CONTINUUM RADIATION AMPLITUDES

The continuum radiation observations in Figure 1 are from the 562-Hz, 1-, 1.78-, 3.11-, and 5.62-kHz channels of the Voyager 1 plasma wave spectrum analyzer and show variations in the amplitude of the radiation on time scales of a few to several hours. Two major effects can be seen in this figure. First, there are dramatic changes in the lower frequency cutoff of the emission; the emission disappears altogether for a few hours at fairly regular intervals. This effect was discussed in detail by Gurnett et al. [1980]. The disappearance of the emission in the early portion of the plotted interval at the lower frequencies such as 562 Hz and 1 kHz reflects the passage of the spacecraft into the relatively high density plasma sheet where the local plasma frequency is large enough to prevent the propagation of low frequency radio waves. Gurnett et al. used this fact to map the position of the plasma sheet and boundary layer.

A second type of temporal variation evident in Figure 1 is the variation in amplitude of the emission which can be seen to some extent in each of the channels represented. This type of variation is not simply a cutoff effect such as is seen at 562 Hz; the minima in signal strength do not drop to the receiver threshold as during propagation cutoffs discussed above. It is this amplitude variation which is the subject of this paper. Clear evidence can be seen in Figure 1 for 10- and even 5-hour periodicities in the amplitude of the radio emission

especially in the 1.78- and 3.11-kHz channels, but also at 1 and 5.62 kHz. Close examination of individual peaks indicates little or no dispersion; the peaks occur at the same time in each channel to within the averaging period. Also, the profile of a typical peak seems to show a rise time which is relatively short compared to the decay time. In the remainder of this study we will focus on the 3.11-kHz channel since this frequency is high enough to be relatively unaffected by the presence of the plasma sheet, yet is low enough so as to be normally trapped in the magnetospheric cavity.

Figure 2 shows 40-minute sliding averages from a 10-day interval during the Voyager 1 outbound passage through the Jovian magnetosphere taken from Kurth [1986]. In this format, the periodic nature of the variation is quite apparent. One can easily see a periodicity of about 10 hours, as well as a definite 5-hour component, especially between days 68 and 70. We should note that such long term averages destroy any evidence of shorter term variations, but our intent is to understand the longer period variations.

Figures 3a and b illustrate the dominant periods seen in the 3.11-kHz channel. Here, we have performed a power spectral analysis of the spectral density plotted in Figure 2 for two different time intervals. In Figure 3a we show that the dominant period, as expected, is near 10 hours for the interval from 0000 spacecraft event time (SCET) on day 65 to 0800 SCET on day 68 1979. Since the interval of analysis is fairly short, we cannot tell if the period is exactly at the System III rotation period of 9 hours, 55 minutes, 29.71 seconds or somewhat different. In Figure 3b the interval analyzed is from 0800

SCET on day 68 through about 1320 SCET on day 70. It is clear that the dominant period here is about 5 hours with a strong peak also near 10 hours. Inspection of Figure 2 verifies that there should be a strong 5-hour component. The other moderate peaks in Figure 3b probably reflect beats between the 5- and 10-hour periods.

Similar results can be obtained by analyzing the Voyager 2 3.11-kHz data. In fact, there seems to be an interval of about two days where the 5-hour periodicity dominates, at about the same radial distance range as that covered by the interval represented in Figure 3b (60 - 100 R_J).

While the 5- and 10-hour periodicities demonstrated above cannot be shown to be exactly at the System III rotation period, it is certainly reasonable to expect some relationship between the peaks and System III longitude. Figure 4 [taken from Kurth, 1986] is a different presentation of the data in Figure 2 organized to show the relationship between amplitude and System III longitude. The data obtained during each rotation of the System III coordinate system are plotted on a grey scale (with black being the most intense) as a function of longitude. Subsequent rotations are plotted in additional strips with later rotations occurring lower in the figure.

It is clear in Figure 4 that while 215° System III longitude is a preferred position for observing the peak in continuum radiation amplitudes, there is a secondary peak near 70° . The magnetic dipole is tilted in the direction of 232° , hence, the dominant peak obviously occurs at high magnetic latitudes. This suggests that the amplitude of the observed emission is simply a function of latitude, or perhaps,

distance from the high density plasma sheet. In fact, one might expect the plasma sheet to affect the observed amplitude since the radio waves are at frequencies that are not much greater than the plasma frequency in the sheet. Refraction effects could be considerable except at positions well separated from the sheet.

To explore the possibility of the effect of the plasma sheet it is necessary to identify the relative position of the amplitude peaks and the plasma sheet. Using the same technique as Gurnett et al. [1980] we have found the System III longitudes of minima in the continuum radiation amplitude at 562 Hz as indicators of plasma sheet location. These positions versus radial distance have been plotted in Figure 5 for the Voyager 1 data set. There appears to be a weak trend for plasma sheet crossings to occur at larger System III longitudes at greater distances. This lag in the sheet crossing time is well documented in the literature. In fact, the dashed line in Figure 5 is from Goertz [1981] and is defined as

$$\delta(R) = 22^\circ + 0.8(R-16.3). \quad (1)$$

In Equation 1 R is the radial distance from Jupiter in Jovian radii. Goertz demonstrated that various plasma, magnetic field, and plasma wave indicators of plasma sheet crossings would be symmetric about the line $\delta(R)$. The plasma sheet crossings as determined by the 562-Hz minima are reasonably symmetric about the line, indicating the low frequency cutoff of the continuum is a reliable indicator of the plasma sheet.

In Figures 6a and 6b we have plotted the positions of the relative maxima of continuum radiation amplitudes at 3.11 kHz as a function of radial distance and System III longitude for Voyager 1 and 2, respectively. Referring for the time being to only the '+' symbols representing data from the outbound trajectory, it is quite evident that the continuum peaks are not influenced by the relative position of the current sheet. In fact, in Figure 6a the Voyager 1 peaks are seen at two relatively constant longitudes of about 70° and 215° . Figure 6b shows a similar result from Voyager 2, however, the longitudes for the peaks are closer to 104° and 246° in this case. For both data sets there is considerable scatter at distances less than about $60 R_J$. The average locations of the peaks for both spacecraft mentioned above are those using only the points beyond about $60 R_J$. We will discuss the possible significance of the shift to larger longitudes of the Voyager 2 set with respect to the Voyager 1 data set below.

The determination that the relative position of the plasma sheet does not affect the observed amplitude of the continuum radiation and that the peaks are seen at nearly constant System III longitudes implies that the amplitude modulation is associated not with the location of the observer but with the position or state of the source. In fact, these observations suggest that the source may be rotating with the planet much as a searchlight since the peaks are observed at nearly constant System III longitude. If the source were rotating with the planet, one would expect to see maxima in the inbound observations of continuum align at the same longitudes as those observed during the outbound passages. In fact, this does not appear to be the case. The

data seem to be better organized by shifting the inbound observations by an angle corresponding to the difference in local time of the inbound and outbound trajectories. In Figures 6a and 6b the positions of the inbound continuum radiation maxima are plotted with solid circles and have been shifted by 100° for Voyager 1 and 120° for Voyager 2. This organization suggests that the continuum amplitudes peak when the Jovian magnetic dipole is oriented in specific directions with respect to the sun and that the radiation is modulated in a clock-like fashion as opposed to being swept around as a searchlight.

Since the number of inbound peaks is limited in both encounters and the radial distances of the inbound points are generally within the range less than $60 R_J$ where the scatter is greatest, it must be said that the improvement in organization of the data by shifting as described above is not spectacular. It is reassuring, however, that treatment of the data sets from both encounters in the same way yields consistent results; both data sets taken separately seem to imply that it is the orientation of the dipole in local time which is important.

Further supportive evidence that the orientation of the magnetic dipole in local time is important is the fact that for the outbound data sets, the preferred Voyager 1 System III longitude is 25 or 30 degrees less than that for Voyager 2. The difference in local time between the two outbound trajectories is about 1 and two-thirds hours or 25 degrees. Hence, the shift in preferred longitude is almost entirely compensated for by the change in local time of the trajectories.

The above analysis of the circumstances under which the continuum radiation is observed to be at maximum intensity implies that the preferred orientation of the dipole is with the sun over the 95th magnetic (System III) meridian. Every time this geometry is achieved, the emission intensity is at its peak. Hence, the emission is modulated in clock-like fashion. A secondary peak is often seen when the sun is over the 315th meridian.

III. DISCUSSION

The amplitude modulation of the trapped Jovian continuum radiation is somewhat surprising in that the emission is generally trapped within the magnetospheric cavity, hence, local intensifications are rapidly distributed through the cavity via multiple reflections and an observer sees a roughly spatially-averaged intensity. The cavity would act as a crude filter. On the other hand, there are very few magnetospheric phenomena which do not show some periodicity related to the spin of the planet, so we should not be too surprised to see that the continuum radiation follows suit. Perhaps the most surprising result is that what is thought to be a distributed source could be organized to the extent of producing reproducible amplitude profiles.

The real issue here is to determine what the periodicity says about the generation of the radio emission and, more importantly, the processes which proceed in the magnetosphere. Unfortunately, since these observations are remote and we can only surmise (by the frequency of the emission and models of the plasma frequency) the location of the widely distributed source, it will be very difficult to draw any definite conclusions about the generation mechanism.

To avoid a detailed discussion of generation mechanisms, let it suffice to say that it is generally quite well accepted that the continuum radiation is generated via mode conversion from intense electrostatic waves near the upper hybrid resonance frequency [Kurth et

al., 1981] through either a linear mechanism [see, for example, Jones, 1976] or a nonlinear mechanism [see, for example, Melrose, 1981]. Consequently, the radiation near 3 kHz is thought to be emitted in numerous narrow bands from upper hybrid waves located on the density gradient either on the outer edge of the Io torus (middle magnetosphere source), or just inside the magnetopause [Scarf et al., 1981; Gurnett et al., 1983] (magnetopause source).

From the variation of plasma frequency with radial distance [see for example, Gurnett et al., 1981] we can locate the middle magnetosphere source of 3 kHz emissions in a rather broad range of distances around $25 R_J$ (if the source is in the plasma sheet) or perhaps much closer to Jupiter if the source is north or south of the sheet where the plasma frequency is smaller at a given distance. This places the source beyond the Io torus; most likely on density gradients either on the extreme outer edge of the torus or north or south of the plasma-sheet (or torus). If one assumes that the source is in the middle magnetosphere, there must be a connection to field lines which thread the outer magnetosphere, close to the magnetopause, due to the apparent importance of the dipole-solar wind alignment. The lack of direct overlap of these two sets of field lines requires an indirect connection from the solar wind to the source region to explain the modulation by the dipole orientation with respect to the solar wind. One might be able to envision periodic injections of few-keV electrons or perhaps enhanced currents providing the connection of the inner magnetosphere to the region near the magnetopause. Or perhaps there could be modulations of the magnetopause size or shape which might result from the

rotation of the offset, tilted dipole. These gross configurational changes could result in a type of micropulsation which could enhance the radio wave production by some as yet unknown mechanism.

The other possible source region is near the magnetopause, itself. It is easy to imagine that periodic variations at the solar wind interface could modulate the intensity of waves generated near this boundary. Hence, we are compelled to consider the magnetopause an important source of continuum radiation, if not the primary source. Observations of upper hybrid emissions near the magnetopause [Gurnett et al., 1979; 1983] support this region as the location of the source. Kurth et al. [1980] cite little evidence for the electrostatic source emissions either at the magnetic equator near 25 R_J or north or south of the plasma sheet (torus) closer to Jupiter.

The modulation of continuum radiation intensities has some interesting implications on the various models explaining temporal variations in Jupiter's magnetosphere. These various models are discussed extensively by many authors [see, for example, Schardt et al., 1981; Vasyliunas and Dessler, 1981; Hill et al., 1983; Schardt and Goertz, 1983]. The three primary models are the clock, the magnetic anomaly, and the disc models. In fact, all three models are used to explain one or more periodic variations observed in the Jovian magnetosphere. One phenomenon which is quite relevant to this paper is the clock-like modulation of Jovian high energy ($> \text{few MeV}$) electrons [Schardt et al., 1981]. These electrons seem to be released when System III longitude $\lambda_{III} = 240^\circ$ points in the tailward direction ($\lambda_{III} = 60^\circ$ is the subsolar longitude). This phenomena is the classic application

of the clock model because the observation of the phase of the electron flux variations is independent of the observer's location. Supporters of the magnetic anomaly model argue their model provides the longitudinal asymmetry required to trigger the electron releases due to some preferred orientation of the anomaly with the solar wind interface--most likely the dawn magnetopause [Vasyliunas and Dessler, 1981; Schardt et al., 1981]. The disc model is clearly ruled out by the fact that only the 10-hour period is evident in the electron fluxes.

Five hour periodicities, as are observed in the continuum radiation peaks, are usually associated with the disc model. For a restricted range of observer latitudes, the magnetodisc will sweep over the observer twice per planetary rotation thereby providing a five-hour periodicity to a number of measurements sensitive to the plasma and/or fields in the disc. There are variations on this model which involve adding bending and finite propagation times to a purely rigid disc model.

The continuum radiation variations, then, combine a key ingredient of the disc model (a rotating, tilted dipole) with the clock model (wherein a fixed orientation with the solar wind is important). The continuum radiation seems to be controlled by a fixed orientation of the dipole with respect to the sun as is the case in the clock model, but also shows a second harmonic component which is indicative of the disc model. Hence, we may see a connection between two of the existing models of the Jovian magnetosphere operative in the modulation of continuum radiation amplitudes. The influence of the solar wind interface tends to emphasize the importance of the magnetopause source

of continuum radiation; and Schardt et al. [1981] have already pointed out the likelihood that the 'clock' electrons are released from the region of the dawn magnetopause, strongly suggesting a tie between the two processes.

Note added in proof: As we were completing this manuscript, we received a copy of Leblanc et al. [1986] which has been submitted to this journal. Leblanc et al. have analyzed the lower frequency (1.2 kHz) emission which shows obvious cutoff effects due to periodically crossing the plasma sheet as shown in Figure 1 of this paper. Analysis of the 562-Hz and 1.0-kHz data presented in Figure 1 would fully support the findings of Leblanc et al. While the periodicity noted at these lower frequencies are not related to those presented herein at higher frequencies, we are pleased to note that Leblanc et al. also conclude that the magnetopause is likely the primary source region for continuum radiation, albeit by a different line of reasoning.

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FIGURE CAPTIONS

- Figure 1 16-minute averages of the electric field spectral density from several of the Voyager 1 plasma wave spectrum analyzer channels during the passage through the predawn Jovian magnetosphere. Amplitude variations at lower frequencies during the first few days can be attributed to propagation cutoffs as the spacecraft passed through the high density plasma-sheet. The remaining periodic amplitude variations are the subject of this report.
- Figure 2 40-minute sliding averages of the Voyager 1 3-kHz spectral densities showing strong modulation at both 10- and 5-hour periods [from Kurth, 1986].
- Figure 3 Power spectral analysis of data presented in Figure 2. (a) Analysis of an interval taken from the early part of Figure 2 showing strong modulation at about a 10-hour period. (b) Analysis of another interval showing strong modulation at periods near both 5 and 10 hours.
- Figure 4 Wave intensity as a function of λ_{III} (abscissa) and rotation number (ordinate) showing intensity maxima at about 70° and 215° . Data are from the Voyager 1 3.11-kHz channel for the interval plotted in Figure 1 [from Kurth, 1986].

Figure 5 Locations of plasma sheet crossings (+) as a function of λ_{III} and radial distance based on minima in the continuum radiation amplitude in the 562-Hz channel of Voyager 1. The dashed line is from Goertz [1981] and is related to the line of symmetry of sheet crossings (see text).

Figure 6 (a) Locations of continuum radiation peaks in λ_{III} and radial distance for the inbound (•) and outbound (+) portions of the Voyager 1 encounter. The inbound points have been shifted by 100° to account for the difference in local time of the two legs of the trajectory. Notice that the peaks remain fixed in longitude and are not related to sheet crossings (which would be symmetric about the line $\delta(R)$).

(b) Same as in (a) but for the Voyager 2 encounter. The peaks lie at longitudes about 25° or 30° higher than for the Voyager 1 peaks.

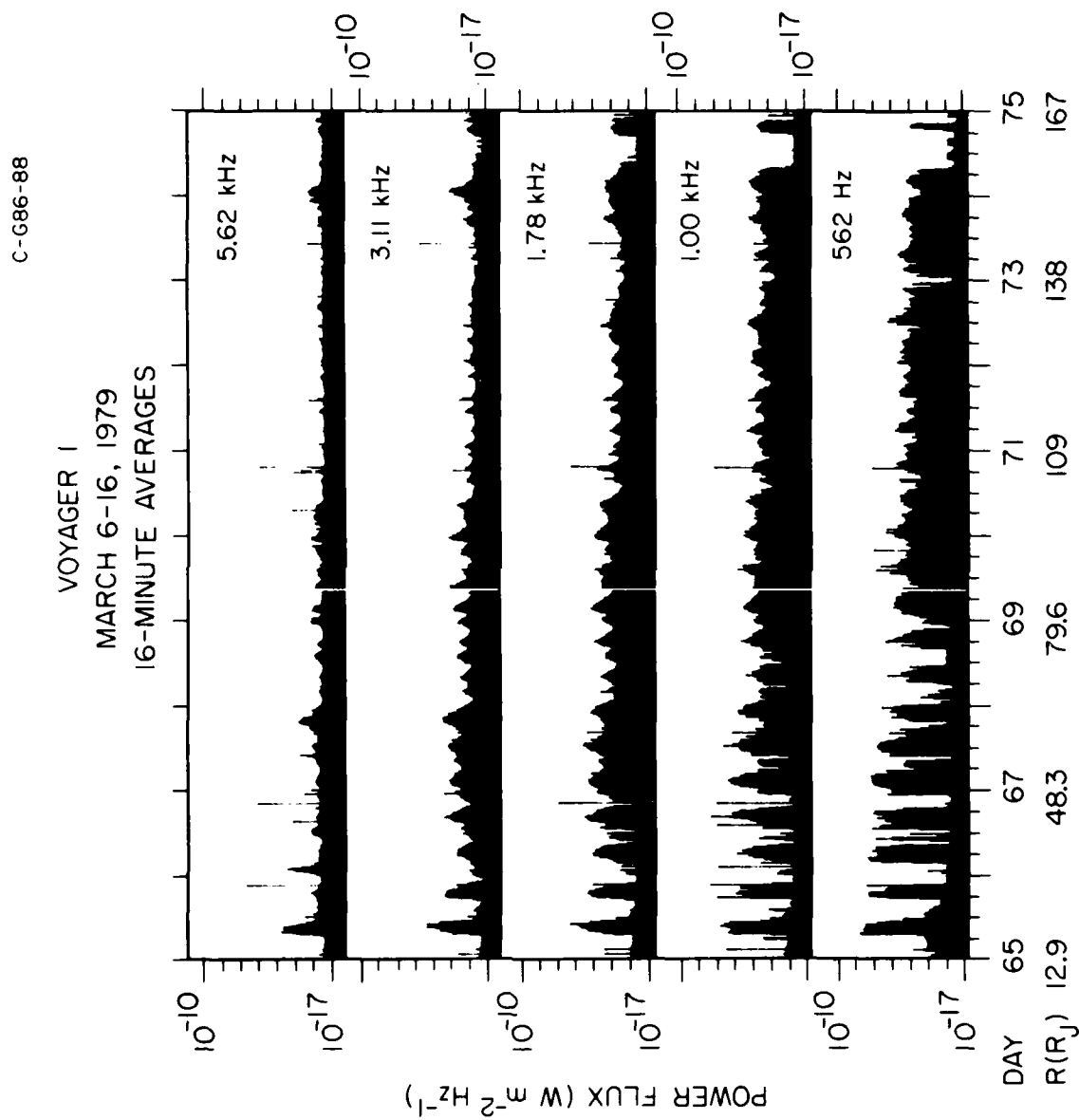


Figure 1

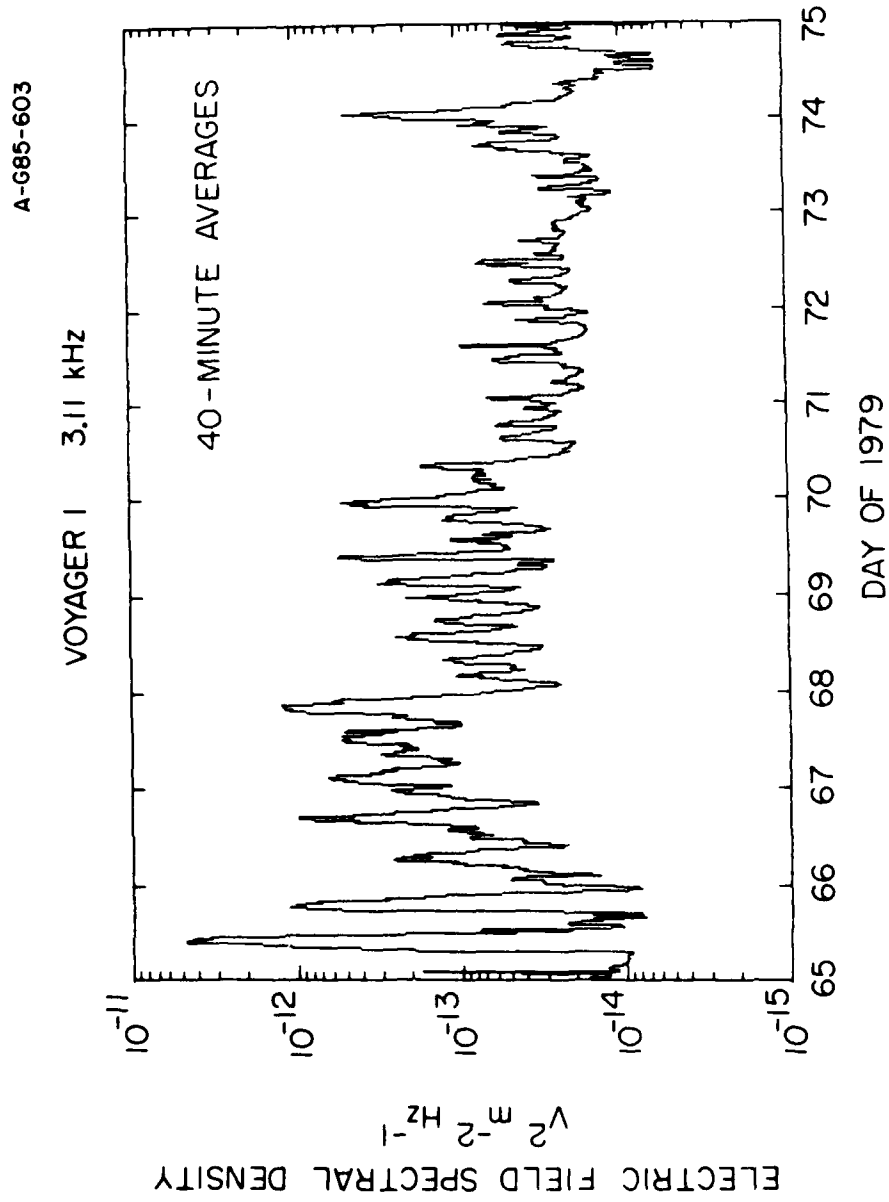


Figure 2

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VOYAGER I 3.11 KHZ

1979 DAY 65 0000 - DAY 68 0800 SCET

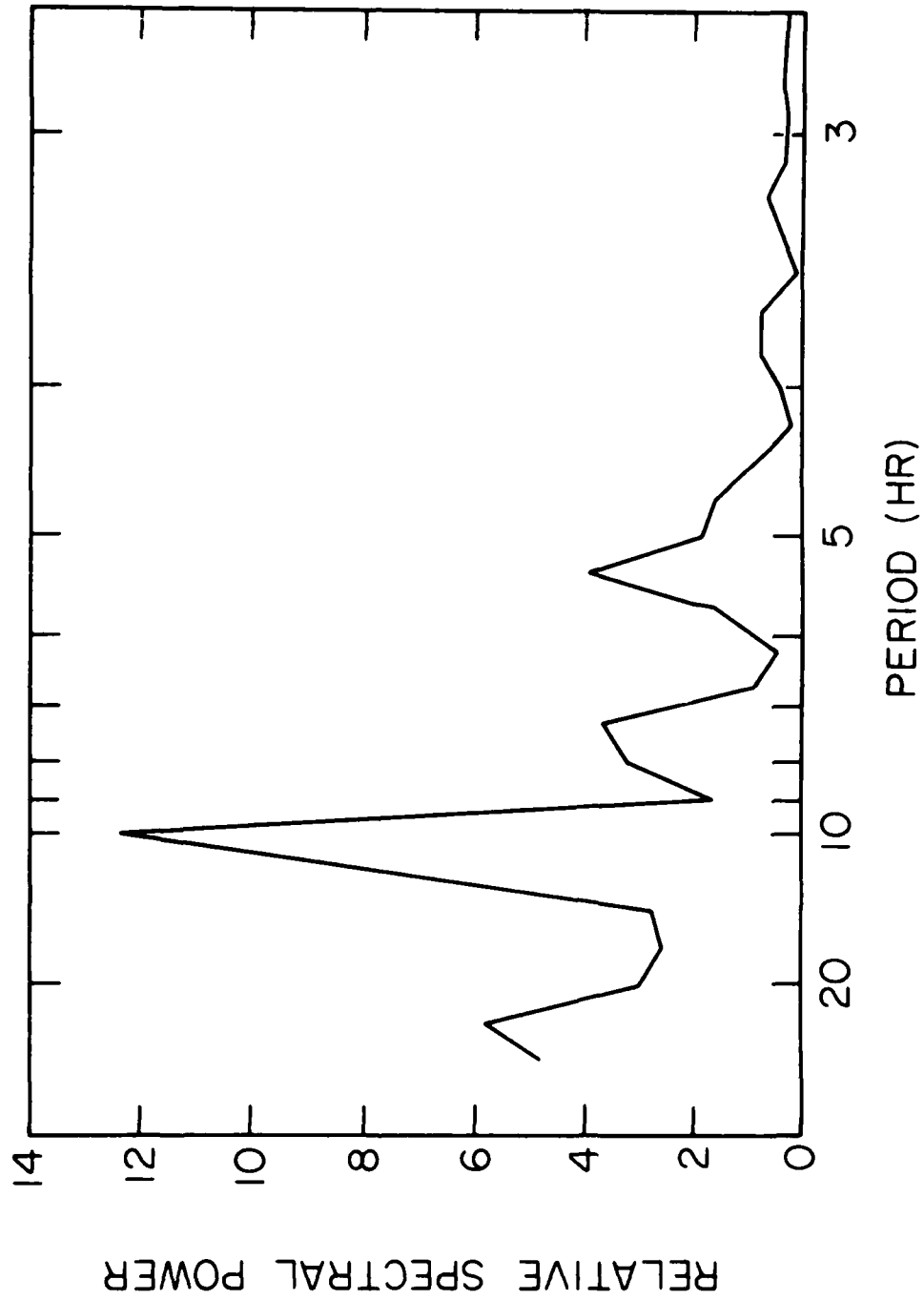


Figure 3a

A-G85-953

VOYAGER I 3.11 kHz

1979 DAY 68 0800 - DAY 70 1320 SCET

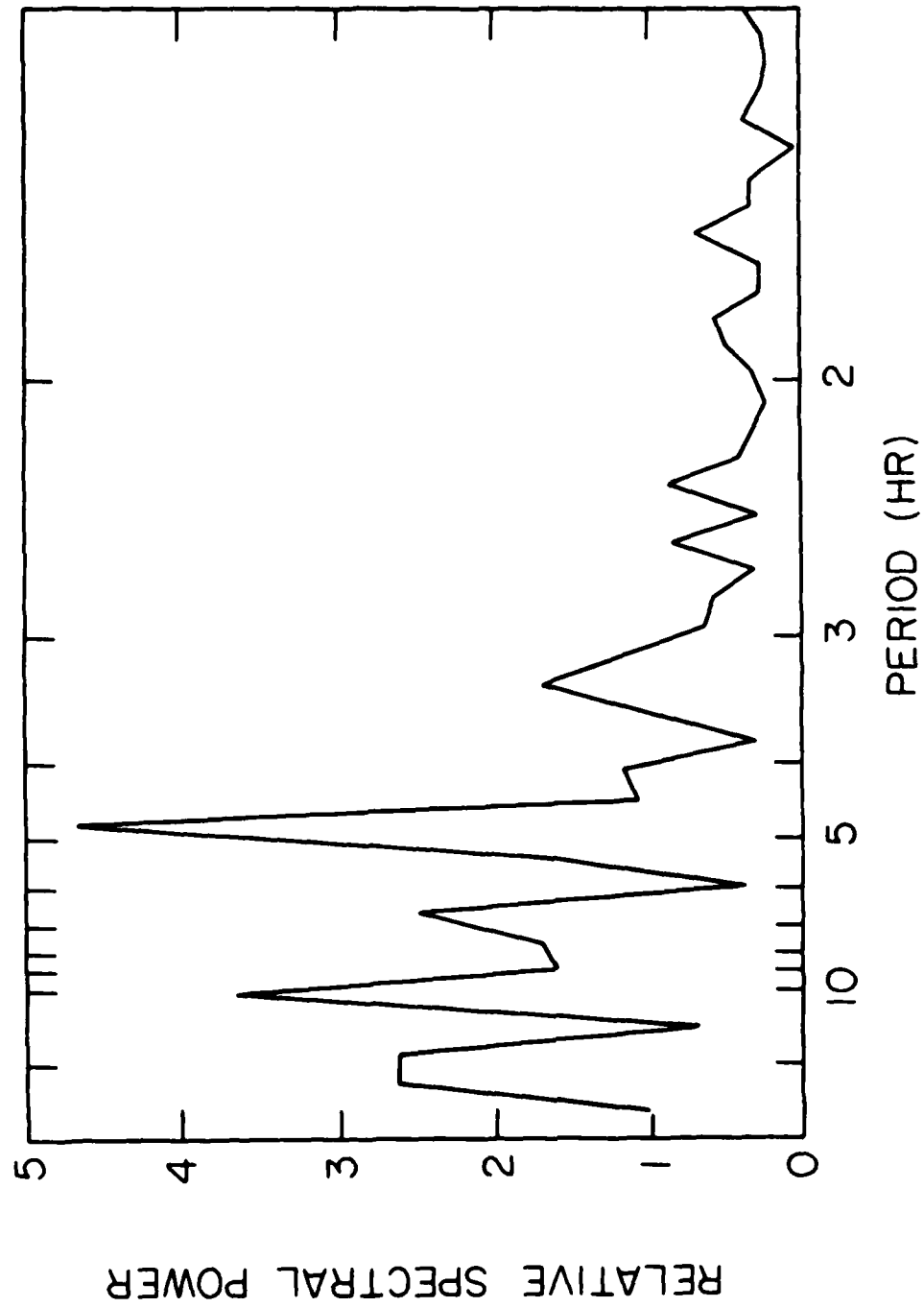


Figure 3b

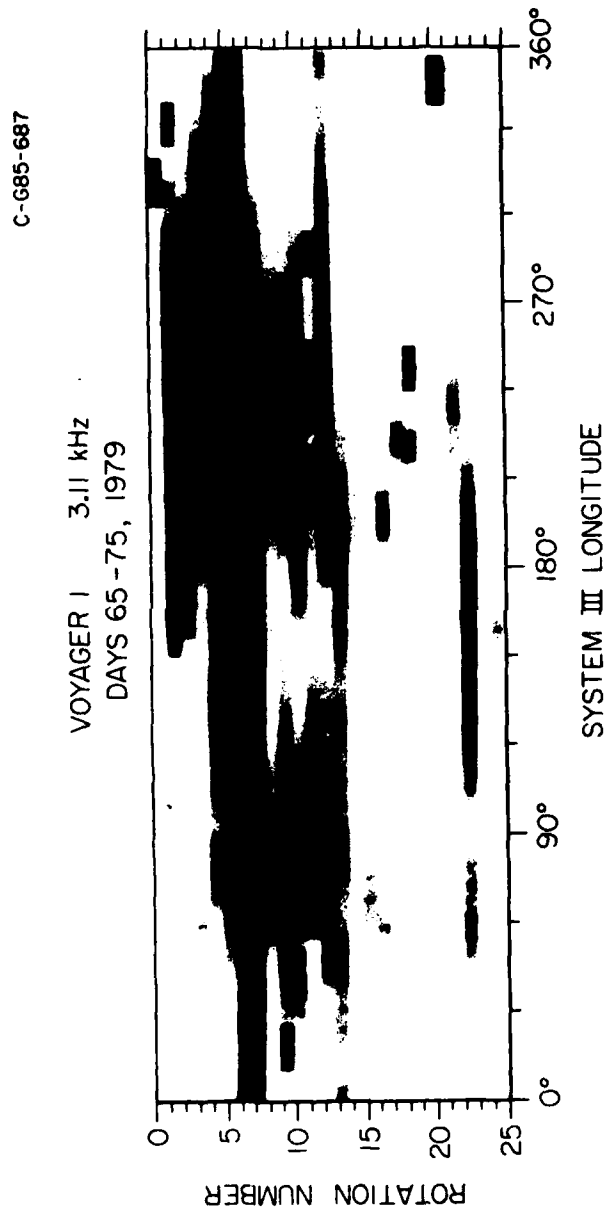


Figure 4

A-G85-994-I

VOYAGER I OUTBOUND
PLASMA SHEET CROSSINGS
562 Hz

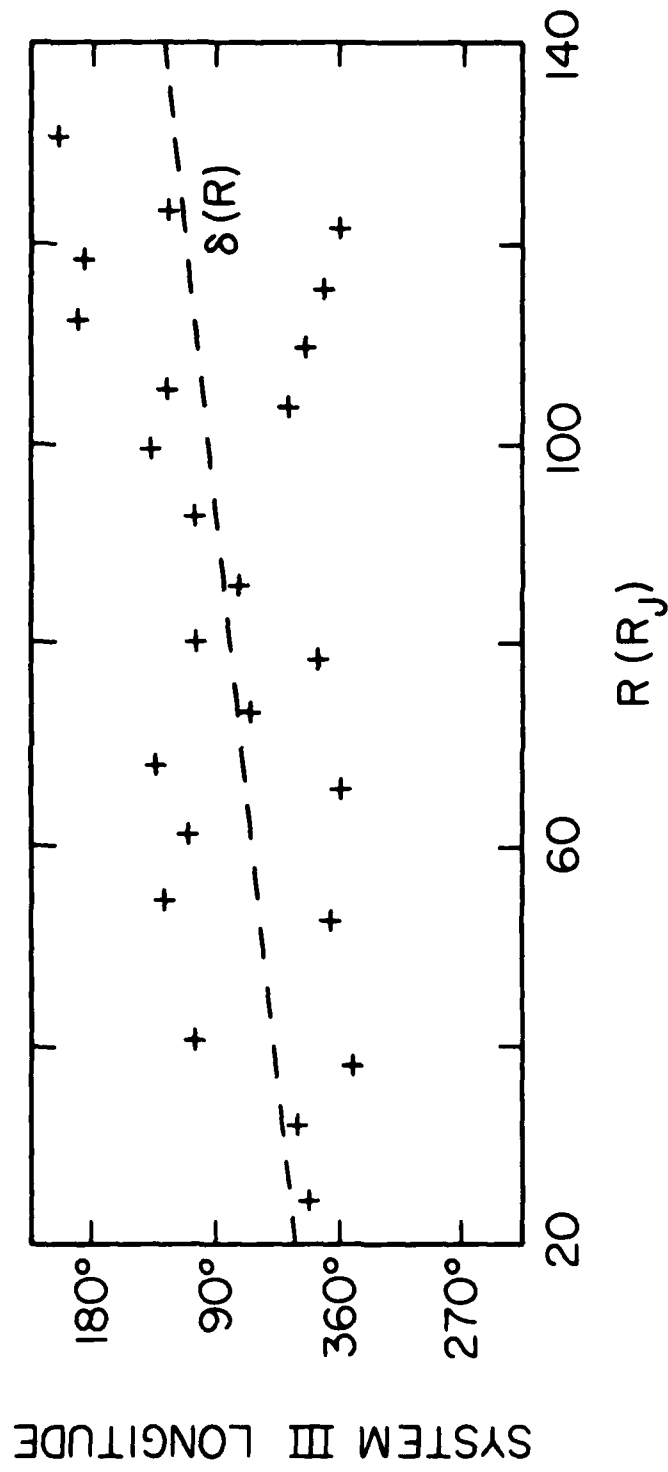


Figure 5

A-G85-993-I

VOYAGER I 3.11 kHz
CONTINUUM RADIATION PEAKS

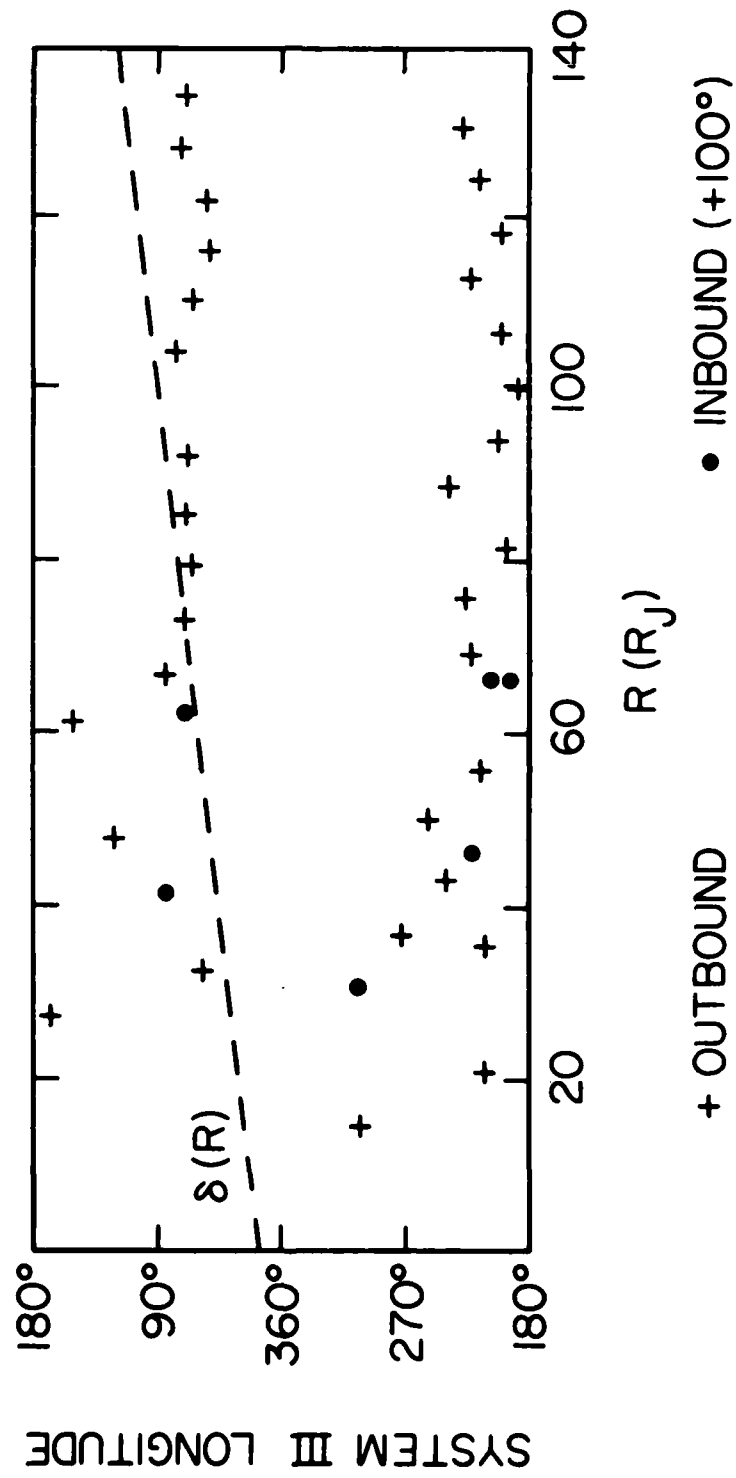


Figure 6a

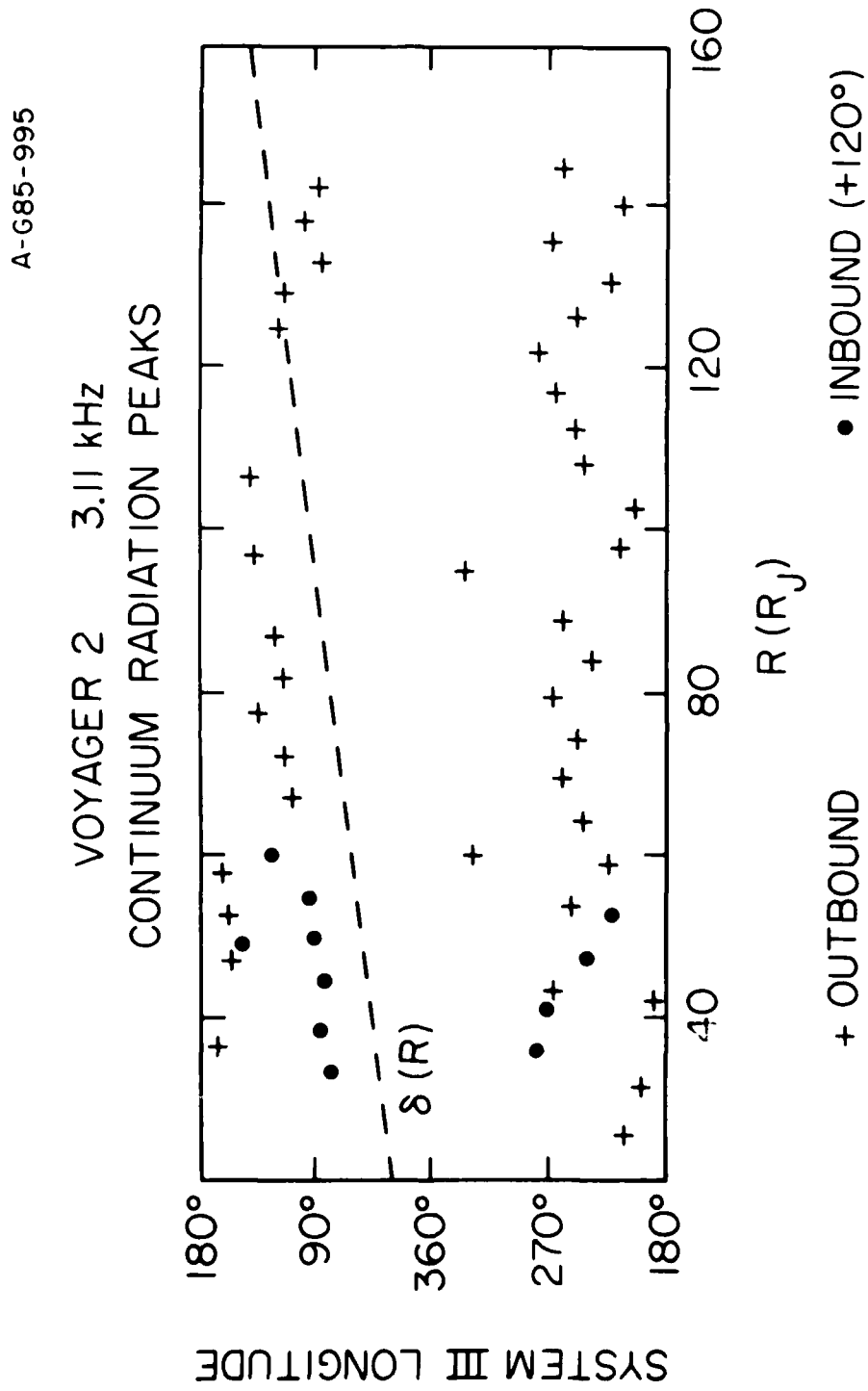


Figure 6b

END

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